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TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

January 1, 1988

Georgia Institute of Technology
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This is an annual report on research conducted under the auspices of the Joint Services Electronics Program. Specific topics covered are: digital signal processing, parallel processing architectures, two-dimensional optical storage and processing, hybrid optical/digital signal processing, electromagnetic measurements in the time domain, and automatic radiation measurements for near-field and far-field transformations.

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Contents

1 Overview

This annual report covers the first year of research carried out under Contract DAAL-03-87-K00059. The research is part of the Joint Services Electronics Program and is administered by the U. S. Army Research Office. Research activities in this program are concentrated in the areas, (1) Two-Dimensional Signal Processing (2) Theory and Application of Electromagnetic Measurements.

The research in two-dimensional signal processing is carried out in five work units. These work units are complementary, and research activities interact and reinforce one another. Research in Work Unit One, *Iterative Signal Restoration and Estimation*, and Work Unit Two, *Representation, Coding, and Analysis of Images*, is concerned with the theory, design, and implementation of multidimensional digital signal representations and digital signal processing algorithms and systems. Work Unit Number Three, *Multiprocessors for Digital Signal Processing*, focuses upon hardware and software problems in the use of multiport memories, VLSI, and multiple processors for high-speed implementations of digital signal processing algorithms. The research in Work Unit Four, *Two-Dimensional Optical Information Processing*, is concerned with problems of using holographic information storage as the basis for multiport memories and for optical computation. Work Unit Five, *Two-Dimensional Optical/Electronic Signal Processing*, is concerned with the theory, implementation, and application of combined optical and electronic digital signal processing techniques. The other two work units in the JSEP program are concerned with electromagnetic measurements. In Work Unit Six, *Electromagnetic Measurements in the Time- and Frequency-Domains*, research is concerned with both theoretical and experimental investigations of the use of time-domain and frequency-domain methods for measuring the characteristics of materials and electromagnetic systems. Work Unit Seven, *Automated Measurements for Near- and Far-Field Transformations*, is concerned with assessing the accuracy of computed fields on the surface of lossy radomes and with compensating for probe effects when near-field measurements are made on spherical and arbitrary surfaces.

The report begins with a summary of the most significant accomplishments (in the judgment of the lab directors) during the period January 1, 1987 to December 31, 1987. Following this are brief reports on the individual work units. These reports list personnel supported and discuss in general terms the research that was carried out during the reporting period. Also included in each work unit report is a complete list of publications on the research during this period. These publications are reprinted in the Annual Report Appendix, which is available in micro-fiche form as a separate document.

2 Significant Research Accomplishments

The following accomplishments are, in the judgment of the laboratory directors, of particular significance and potential and are therefore worthy of special mention.

2.1 Periodic Scheduling Theory for DSP Multiprocessors

In prior work under JSEP, three optimal periodic scheduling methods were developed: *skewed single instruction multiple data* (SSIMD), *cyclo-static*, and *Multi-Cyclic Instruction Multiple Data* (MCIMD). The latter is an extension of cyclo-static schedules based primarily on the use of heterogeneous processing elements. Recent work has resulted in the unification of SSIMD, cyclo- static and MCIMD as well as the more traditional scheduling methods of Critical Path Method (CPM), As Soon/Late As Possible (ASAP/ALAP), systolic array schedules, and static pipeline schedules. The new work has shown that all of these schedules can be represented in a single unified form based on a *period matrix* and a *cycling vector*. Furthermore, it has been shown how to transform the a schedule into any of the other classes of schedules. The importance of this unification is that it shows that the generalized SSIMD schedule is the optimal class for homogeneous processors and that generalized *parallel SSIMD* (PSSIMD) is the optimal class for heterogeneous processors. This powerful conceptual framework has already led to a simplified representation of schedules and a corresponding simplification of the scheduling algorithm. Based on this result, a preliminary, general purpose, parallel processing architecture based on a low order chorded ring has been proposed.

2.2 Zero-Reflectivity Surface Relief Gratings on Lossy Materials

The thickness and complex refractive index of single homogeneous layers on lossy substrates that are required to produce zero reflectivity have been calculated by a rigorous impedance matching approach. The analysis is applicable to both TE and TM polarization and to any angle of incidence. The method permits the filling factor and the groove depth of a rectangular-groove grating equivalent to a single homogeneous lossy layer in the long wavelength limit to be calculated. The method reduces to that previously found for dielectric surface-relief gratings in the limit of no losses. The anti-reflection behavior has been verified for the gratings using the rigorous (without approximations) coupled-wave analysis of metallic surface-relief grating diffraction. Multiple zero-reflectivity solutions exist for both TE and TM polarizations and for any angle of incidence for an arbitrary complex-refractive-index substrate. The theory has been verified experimentally through fabrication of zero-reflectivity gold gratings for an incident freespace wavelength in the range from $\delta_0 = 0.44\mu m$ to $12.0\mu m$. For the longer wavelengths, the behavior of the gold approaches that of a perfect conductor and the required filling factor approaches zero for TE polarization and unity for TM polarization.

2.3 Shaped Edge Serrations for Improved Reflector Performance

A new edge treatment for electromagnetic reflectors has been developed that produces less wide angle scattering than previously used edge treatments. The new edge treatment allows a wide variety of field transition functions to be realized in an average sense. This new technology has been applied to the design of an improved compact antenna range reflector, resulting in a lower cost, better quiet zone performance range. This range is currently under construction at Ft. Huachuca, Arizona. This technology is currently being applied to the design and construction of a paraboloidal reflector antenna to achieve low, wide angle, sidelobe levels.

Work Unit One

TITLE: Iterative Signal Restoration and Estimation

SENIOR PRINCIPAL INVESTIGATORS:

Russell M. Mersereau, Regents' Professor and Rockwell Fellow
Monson H. Hayes III, Associate Professor

SCIENTIFIC PERSONNEL:

C. AuYeung, Graduate Research Assistant (Ph.D. Expected June 1988)
S. Reeves, Graduate Research Assistant (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The objective of this research is to study and develop a broad class of iterative signal restoration techniques to remove linear and non-linear degradations from signals through a knowledge of the distortion operator and the class of allowable signal. This work brings together ideas from signal processing, functional analysis, optimization theory, statistical filtering, and signal modeling.

RESEARCH ACCOMPLISHMENTS:

- *Quadratically Convergent Deconvolution Algorithms*

Iterative algorithms based on the method of successive approximations have become very popular for signal deconvolution due to the flexibility that they allow for the incorporation of signal constraints into the restoration. One of the limitations of these iterative algorithms, however, is that they only achieve a linear rate of convergence. This work has been concerned with the development and analysis of a new method for accelerating the rate of convergence of the standard iterative reconstruction algorithms. The primary limitation with this algorithm is the lack of formal methods for imposing constraints on the solution. Although several ad hoc approaches have been developed for imposing a positivity constraint, these methods have met with only limited success. The work on this project has been completed and the primary research results are summarized in a paper that has recently been accepted for publication.

- *The Phase Retrieval Problem*

Phase retrieval is a long-standing problem with applications in many different areas. So far, the success in reconstructing an arbitrary two-dimensional image from spectral

magnitude information alone has been limited. Therefore, we have begun to focus on the problem of reconstructing a two-dimensional image from multiple spectral magnitude functions. Therefore, it builds upon the earlier JSEP research by Katsaggelos who studied the problem of reconstructing an image from more than one linearly distorted observation. Here, we are investigating the reconstruction of an image from a set of nonlinearly distorted images, i.e., two or more magnitude-only images. Although this work is in the early experimental stage, some encouraging results have been obtained.

- *Signal Modeling and Power Spectrum Estimation*

Power spectrum estimation is a special form of signal reconstruction problem in which the autocorrelation function or its Fourier transform is to be recovered from a finite time observation of a time series or from a truncated noisy autocorrelation sequence. Therefore, we have been studying two problems related to signal modeling and the application of these models to spectrum estimation. The first is the development of an ARMA lattice filter for time-varying system identification. This work has generalized the structure and properties of all pole lattice methods and has led to a number of interesting and important research results that have culminated in a Ph.D. thesis.

Based on our long-standing interest in constrained iterative deconvolution algorithms, we applied our experience with these problems to the problem of estimating the power spectral density of a stationary two-dimensional random processes. In particular, we developed an iterated Toeplitz approximation method (ITAM) that simultaneously imposes a Toeplitz constraint and a fixed rank constraint on a measured autocorrelation matrix. The goal is to find a low rank Toeplitz matrix that is as close as possible to a given measured autocorrelation matrix. It was shown that with the use of ITAM as a preprocessor in two-dimensional harmonic power spectral estimation algorithms, improved frequency estimates are possible.

- *Constrained Iterative Image Deblurring*

This long-standing research area was wrapped up this year with the preparation of a major tutorial paper. This paper summarizes all of the work that we have done. The iterative procedures were shown to perform significantly better at the deblurring task than Kalman filtering, Wiener filtering, or constrained least squares filters, although the latter two could be obtained as special cases when the constraints were disabled. Recent results extended the earlier work to incorporate point-wise non-linearities, spatially adaptive procedures to reduce ringing artifacts, and procedures which incorporated iterations with much faster convergence. The latter were compared in a presentation at the 1987 IEEE International Conference on Acoustics, Speech and Signal Processing.

- *Maximum Entropy Image Restoration*

Work has continued on the development of formalisms for the constrained restoration of multidimensional signals under a variety of optimization criteria. This work unifies, extends, and corrects existing procedures for least squares, maximum entropy, and minimum cross entropy techniques under a number of different types of techniques. These algorithms are currently being applied to the problem of signal reconstruction from projections and an application of this work in geophysical tomography has recently been submitted for publication. This application is directed towards the problem of mapping subterranean features. Maximum entropy restoration also appears to be well suited to the resolution of multiple impulsive sources on a uniform background. Such applications occur in radio astronomy and in a number of problems in target detection. A thesis in this area will be completed during the next calendar year.

- *Restoration and Segmentation of Video Sequences*

This is a new effort which grew out of the work on constrained iterative image restoration. The work is extended in two ways: first it is assumed that the blurring operator is not known but that it must be estimated from the blurred imagery itself, and second it is being extended to work on video sequences. The goal here is to be able to effectively segment video data into foreground and background elements and to enhance the visual quality of the objects in the foreground.

PUBLICATIONS:

Journal Articles (published or accepted):

1. C. E. Morris, M. A. Richards and M. H. Hayes, "Iterative Deconvolution Algorithm with Quadratic Convergence," *Optical Society of America A*, vol. 4, page 200, January 1987.
2. E. Karlsson and M. H. Hayes, "Least Squares ARMA Modeling of Linear Time-Varying Systems: Lattice Filter Structures and Fast RLS Algorithms", *IEEE Transactions on Acoustics, Speech and Signal Processing*, vol. ASSP-35, no. 7, pp. 994-1014, July 1987.
3. C. E. Morris, M. A. Richards, and M. H. Hayes, "Fast Restoration of Linearly Distorted Signals", accepted for publication in *IEEE Transactions on Acoustics, Speech and Signal Processing.*
4. D. M. Wilkes and M. H. Hayes, "Block Toeplitz Approximation and 2-D Harmonic Retrieval", accepted for publication in *Signal Processing.*
5. J. Biemond, R. L. Lagendijk, and R. M. Mersereau, "Iterative methods for image deblurring," to be submitted to the *Proc. IEEE.*
6. P. M. Carrion, C. AuYeung and R. M. Mersereau," A new approach to constrained seismic travel-time tomography," submitted to *Geophysics.*
7. D. M. Wilkes and M. H. Hayes, "Toeplitz Approximation and Linear Prediction for Harmonic Retrieval", submitted for publication in *IEEE Transactions on Acoustics, Speech and Signal Processing.*
8. D. S. Mazel and M. H. Hayes, "Reflections on Levinson's recursion", to appear in *1988 Proc. International Conference on Acoustics, Speech and Signal Processing.*
9. D. M. Wilkes and M. H. Hayes, "Iterated Toeplitz approximation of covariance matrices", to appear in *1988 Proc. International Conference on Acoustics, Speech and Signal Processing.*

Conference Presentations:

1. R. L. Lagendijk, J. Biemond and R. M. Mersereau, "On increasing the convergence rate of regularized iterative image restoration algorithms," *Proc. 1987 IEEE International Conference on Acoustics, Systems and Signal Processing*, pp. 1183-1186, April 1987.
2. C. E. Morris, M. A. Richards, and M. H. Hayes, "A generalized fast iterative deconvolution algorithm," *Proc. 1987 International Conference on Acoustics, Speech and Signal Processing*, pp. 1553-1556, April 1987.

3. D. M. Thomas and M. H. Hayes, "A novel data-adaptive power spectrum estimation technique," *Proc. 1987 International Conference on Acoustics, Speech and Signal Processing*, pp. 1589-1592, April 1987.

4. E. Karlsson and M. H. Hayes, "Performance analysis of new least squares ARMA lattice modeling algorithms", *Proc. 1987 International Conference on Acoustics, Speech and Signal Processing*, pp. 984-987, April 1987.

Work Unit Two

TITLE: Representation, Coding, and Analysis of Images

SENIOR PRINCIPAL INVESTIGATORS:

Ronald W. Schafer, Regents' Professor
Russell M. Mersereau, Regents' Professor and Rockwell Fellow

SCIENTIFIC PERSONNEL:

J. Bevington, Received Ph.D. December 1987
F. J. Malassenet (Ph.D. Candidate)
L. Hertz (Ph.D. Candidate)
C. H. Richardson (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The first major objective of this work unit is to study and develop new approaches to the modeling of images and to the representation of the information contained in images. A second major objective is to use such models and representations to solve problems in automatic extraction of information from images and in efficient digital coding of images.

RESEARCH ACCOMPLISHMENTS:

- *Textured Image Segmentation*

The Ph.D. thesis by Bevington, was completed in November, 1987. It developed a powerful new technique for the estimation of detailed boundaries between image regions which differed with respect to textural properties. It employed causal, autoregressive, Gaussian random field models for the textured regions, and applied the maximum likelihood principle to the problem of determining the region association of individual pixels. The key to the success of this approach was the imposition of local constraints on the region boundaries. These constraints led to the practical implementation of a local maximum-likelihood boundary estimator which was very robust to deviation of the true image data from the assumed models. A version of the estimation algorithm was developed for both the cases of known and unknown a priori model parameters, and the estimator was tested successfully on a number of natural textures.

Boundaries separating an arbitrary number of differently textured regions were estimated by applying a local boundary estimator to non-overlapping windowed portions of the image. The boundary estimator was used to split each window or frame into two or more homogeneous textured regions, after which similar neighboring regions were merged

to form the final estimates. Region similarity was evaluated using statistical distance measures based on the assumed autoregressive models. The segmentation program operates without a priori knowledge of texture model parameters and was tested on images formed from textures taken from the Brodatz album.

- *Fractal Models for Image Texture*

A research study has begun on the use of iterated function systems to model texture and textured regions of an image. The outputs of these systems are deterministic fractals. The early work on this problem has been expended in the development of a software workstation environment for the ultimate performance of the research. It has been used for coding color images with impressive coding efficiencies, but the inability of the coders to render texture has motivated this research project. It is anticipated that in the next year this project will have begun to ask such questions as: What are good metrics for comparing textures? How well can IFS's perform in reproducing a texture? Can the IFS parameters serve as a useful basis for texture discrimination, texture segmentation, and image analysis?

- *Morphological Systems for Processing FLIR Images*

The theory of mathematical morphology is an approach to the representation of images and image processing systems that seeks to quantitatively represent geometrical structure in images. The key to this approach is that signals are represented by sets rather than by functions, and therefore systems (or image transformations) are represented as set transformations. Sets or collections of image points are a much more natural representation for displaying geometrical structure.

Until recently, most of our research on morphological systems has focused on theoretical system analysis and on coding of binary images. However, little effort has been directed at the problem of designing morphological systems to perform a specific function. As a first step toward learning how to design such systems, we considered the problem of filtering man-made objects out of a background of natural objects in FLIR images. Issues considered included the selection of the morphological operations, the choice of shape and size of structuring elements, and the sequence in which the operations were applied. It was found that a sequence of top hat transformations coupled with gradient operations performed well in the task of isolating a single target in a FLIR image. Knowledge gained in this experimental application serves as a useful starting point for the development a more systematic design methodology for morphological systems.

- *Design and Analysis of Morphological Systems*

Previous JSEP-supported research at Georgia Tech has resulted in the development of a general theory of translation-invariant morphological systems. This theory shows that a large class of systems can be represented (and implemented) in terms of simple erosion and dilation operations. Our research has shown that this theory applies to morphological filters, median filters, order-statistics filters, edge detectors, shape recognition transformations and an interesting class of linear shift-invariant systems. Erosion and dilation can also be used to obtain skeleton representations, which display information about size, shape, orientation, and connectivity of image objects. The general representational theory has already lead to new insights into the properties of such systems and also to new approaches to their implementation; however, a design methodology for this class of systems has yet to emerge.

As a first step toward developing a design methodology for morphological systems, we have begun to establish a design/analysis environment capable of performing symbolic and numerical manipulations of complex morphological operators. The symbolic manipulations consist of expression rearrangements and simplifications as well as signal and system analysis using knowledge of the transformations and structuring elements. This involves the use of object-oriented programming techniques for compiling and applying knowledge about morphological operators and their interconnections and for incorporating knowledge of signal properties and system implementation constraints. The numerical processing component of this environment, which uses deferred evaluation of expressions, serves as the base upon which the symbolic processing capabilities are constructed, and provides the means for testing morphological systems on real signals.

This research is still in its early phase, and many issues remain to be addressed before a complete design/analysis environment is available. As appropriate equipment becomes available, the design/analysis environment will be implemented on a high-performance graphics workstation.

- *Multilevel Thresholding for Image Analysis*

Thresholding is an effective method for simplifying images of untextured objects on an untextured background. Multiple thresholds are required when thresholding images containing several objects of differing brightness or reflectivity. Also, to account for variations of grey levels due to non-uniform illumination, it is often necessary to allow the thresholds to vary adaptively across the image. A technique called *edge matching* has been developed for adjusting multiple thresholds so that the edges of the thresholded image closely match the edges of the original grey-tone image. The result is a thresholded image that preserves the shapes and and geometrical structure of the objects in the image. The resulting multilevel image can be "sliced" to extract objects that occupy the different threshold bands. Morphological systems can then be used to process the slices of the multi-threshold image.

- *Automated Image Analysis*

In many image analysis problems, considerable a priori knowledge is available about the image being analyzed. This is the case in many problems in computer vision, automated inspection, surveillance, and automatic target tracking. Often the information is in symbolic form, such as instructions for drawing a printed circuit board layout or an integrated circuit mask. Thus, interesting problems arise in combining the symbolic information with the numeric representation of a digitized image. This is particularly true when the image field of view is more restricted than the symbolic representation, and it is necessary to determine which part of the object or scene is in view.

Preliminary investigations of problems of this sort have been carried out with encouraging success. Specifically, PC boards represented in the Cal Tech Intermediate Format (CIF) have been fabricated and subsequently imaged. Techniques have been developed that successfully extract a CIF-like representation of the image. Research is now progressing on techniques for efficiently comparing the symbolic representation of the image with the symbolic representation that was used in the original fabrication.

This work has obvious applications in automated visual inspection of electronic circuits, and it may generalize to other types of problems such as situations where a map showing terrain or physical features may be available to compare to images of the locale covered by the map.

PUBLICATIONS:

Theses:

1. J. E. Bevington, " A Statistical Model-Based Approach to Textured Image Segmentation," *Georgia Institute of Technology, School of Electrical Engineering*, November, 1987.

Journal Articles (published, submitted or accepted):

1. P. A. Maragos and R. W. Schafer, "Morphological Filters - Part I: Their Set-Theoretic Analysis and Relations to Linear Shift-Invariant Filters," *IEEE Trans. Acoustics, Speech, and Signal Processing*, vol. ASSP-35, pp. 1153-1169, Aug. 1987.

2. P. A. Maragos and R. W. Schafer, "Morphological Filters - Part II: Their Relations to Median, Order-Statistic, and Stack Filters," *IEEE Trans. Acoustics, Speech, and Signal Processing*, vol. ASSP-35, pp. 1170-1184, Aug. 1987.

3. K. Nishikawa and R. M. Mersereau, "Design of circularly symmetric two-dimensional IIR lowpass digital filters using McClellan transformations," submitted to *IEEE Transactions on Acoustics, Speech and Signal Processing.*

4. L. Hertz and R. W. Schafer, "Multi-Level Thresholding Using Edge Matching," submitted to *Computer Graphics and Image Processing.*

Conference Presentations:

1. J. E. Bevington and R. M. Mersereau, "Differential operator based edge and line detection," *Proceedings of the International Conference on Acoustics, Speech and Signal Processing*, vol. 1, pp. 249-252, Dallas, Texas, April, 1987.

2. C. H. Richardson and R. W. Schafer, "Application of Mathematical Morphology to FLIR Images," *Proc. of SPIE, Visual Communications and Image Processing*, vol. 845, Cambridge, MA, Oct. 1987.

Work Unit Three

TITLE: Multiprocessors for Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATORS:

T. P. Barnwell, III, Professor and Rockwell Fellow
D. A. Schwartz, Assistant Professor

SCIENTIFIC PERSONNEL:

H. R. Forren, (Graduate Research Assistant and Ph.D. Candidate)
P. R. Gelabert, (Graduate Research Assistant and Ph.D. Candidate)
L. P. Heck, (Graduate Research Assistant and Ph.D. Candidate)
C. P. Hong, (Graduate Research Assistant and Ph.D. Candidate)
D. J. Pepper, (Graduate Research Assistant and Ph.D. Candidate)
S. A. Spalding, (Graduate Research Assistant)
K. K. Truong, (Graduate Research Assistant and Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The primary objective of this work unit is to develop systematic techniques for the automatic generation of provably optimal multiprocessor implementations for a broad class digital signal processing (DSP) algorithms and for a broad class of multiprocessors systems. Stated in another fashion, the goal of this research is to develop DSP "compilers," where the input is an algorithm specification and the output is a complete, optimal multiprocessor implementation.

A basic philosophy of this research has always been to perform the theoretical developments in the context of an actual multiprocessor system. The first system used for this purpose, an eight processor LSI-11/2 system, is now obsolete. The current research is being tested using the OSCAR-32, a personal computer (PC) based multiprocessor utilizing the AT&T DSP-32 floating point DSP microprocessor.

BACKGROUND:

Over the past decade, the rapid development of digital integrated circuit techniques has caused increased interest in the area of parallel architectures for digital signal processing. Nowhere is this more evident than in multidimensional DSP algorithms, where the computational intensity of the algorithms make serial processing unreasonable for virtually all real-time applications.

In any DSP oriented implementation, there will inevitably be a mix of both intrinsically serial and intrinsically parallel tasks which must be realized. Digital signal processing algorithms, as a group, are unique in that they are typically both highly computationally intense and also have a high degree of internal structure. For the purposes of this research, a DSP implementation is considered to be a realization which is dominated by its signal processing functions, and in which its non-signal-processing tasks (control, user interface, decision making, etc.) play a relatively minor role.

For most of the past research from this work unit, the DSP algorithms have been specified as *shift-invariant flow graphs* (SIFG). SIFG's are capable of representing a very large class of interesting DSP algorithms. A *fully specified flow graph* (FSFG) is a SIFG in which the nodal operations are additionally constrained to be the atomic (kernel) operations of the underlying constituent proccssors which are to be used in the realization. Thus the atomic operations represent the smallest granularity at which possible parallelism may be exploited. The name *generic flow graph* is used to distinguish between those SIFG's that are also FSFG's and those SIFG's whose nodes are not all atomic operations.

A distinguishing characteristic of our research is the underlying use of bounds on the optimal performance of an algorithm in the generation of the multiprocessor implementations. These bounds are characteristics of the graph defining the algorithm, not of the mechanism or type of realization. In all, three different bounds are used: the *iteration period bound*, which is the minimum possible time between iterations of the algorithm; the *delay bound*, which is the minimum time between the availability of an input (set) and the availability of the corresponding output (set); and the *processor bound*, which is the minimum number of processors required to achieve the specified iteration period. Implementations which achieve the iteration period bound are said to be *rate-optimal*. Implementations which achieve the delay bound are called *delay-optimal*. Implementations which use the minimum possible number of processors for a specified iteration period are said to be *processor-optimal*.

Historically, *Skewed Single Instruction Multiple Data* (SSIMD) implementations were the first class of solutions which could overcome the constraints imposed by systolic systems and consistently achieve rate-optimal, processor-optimal implementations with nearest neighbor communications for a large class of interesting algorithms. In SSIMD, exactly the same program is executed on each of the processors in the multiprocessor, and that program realizes exactly one iteration of the flow graph. In an SSIMD program, all of the arithmetic operations appear as explicit instructions, but the delay nodes are transformed into input-output pairs. In this way, the delay structure in the flow graph becomes the communications structure in the SSIMD realization.

The SSIMD approach to flow graph realizations is very attractive for many reasons. First, for all SSIMD realizations in which the number of processors is less than the processor bound, the implementations are perfectly efficient and the use of N processors always increases the throughput by a factor of exactly N. Second, when the SSIMD iteration period bound is equal to the iteration period bound, as is the case for many recursive digital filter structures, then there exists *no* multiprocessor solution using the same constituent

processor which is faster or more efficient. Third, although the iteration period bound concept is not involved, SSIMD realizations work equally well for non-recursive structures. A significant and unique aspect of SSIMD solutions is that the program for a one processor solution is identical to the program for a P processor solution. The only difference is in the interprocessor communications connections. Finally, and most importantly, the all-important communications architecture for the final implementation is completely specified by the delay node structure of the flow graph. In particular, by constraining all the delay nodes to be first order, all single-time-index (one-dimensional) SSIMD solutions can be realized with a nearest-neighbor unidirectional ring. A similar result applies to two-dimensional flow graphs. However, if a more complex communications mechanism is available, then the flow graph can be defined to take advantage of it.

The next important historical contribution of this work unit was the creation of a cyclo-static compiler for fully specified flow graphs. The development of the cyclo-static compiler really grew out of an attempt to understand why SSIMD and PSSIMD implementations could be rate-optimal, processor-optimal, and communications-optimal while the systolic implementations for the same algorithms could not. There are really two separate reasons for the shortcomings of systolic arrays. The first is the fact that systolic processors are static pipelines. This means that any particular operation in an algorithm is assigned to a particular processor in the systolic array, and that operation is performed by that processor on every iteration. Hence, the operations are static and only the data moves through the multiprocessor. In contrast, SSIMD, PSSIMD, and cyclo-static processors are dynamic pipelines in which both the operations and the data move through the multiprocessor. The second reason is the effect of the global transfer clock. Indeed, this global transfer clock was the basic characteristic for which systolic arrays were named, giving the whole system it's "pumping" action. There is no fundamental requirement that all the pipeline registers in the system be clocked simultaneously. There is also no reason that each processor must perform I/O on every clock cycle. In contrast, the input-output operations in SSIMD, PSSIMD, and cyclo-static implementations move in parallel, non-overlapping wavefronts (with a periodic pattern to the spacing of successive wavefronts).

Cyclo-static implementations are a new class of multiprocessor solutions which can be used for the optimal realization of iterative or recursive algorithms on synchronous multiprocessors. A processor which realizes cyclo-static implementations can be considered to be a generalization of systolic processors, wavefront array processors and SSIMD processors. Cyclo-static realizations differ in that they are provably optimal with respect to multiple criteria.

Cyclo-static solutions can be effectively found that achieve a subset of the following optimality criteria: *rate optimal* (maximally parallel, minimum iteration period), *processor optimal* (maximum processor efficiency), *delay optimal* (minimum throughput delay) and *adjacent communications optimal* (adjacent processor communications only). The procedure for finding solutions is a combinatorial optimization method which is efficient for typical realizations that are rate optimal. This problem was previously considered computationally intractable. In particular, previous researchers who considered optimal

deterministic scheduling of flow graphs took the approach of transforming the original directed cyclic (containing loops) flow graph to a directed acyclic graph (loop free). Unfortunately the optimal solution to the acyclic graph can only fully exploit the parallelism of the original graph for a few special cases. The original aspects of this work are the direct utilization of the original cyclical graph, the concept of applying graph bounds as part of the multiprocessor compilations procedures and the introduction of a new approach to periodic scheduling.

Another set of research results, largely included in the Ph.D. thesis of work Sae Hun Lee, was the presentation of a set of techniques for the generation of optimal multiprocessor realizations from non-parallel (serial) algorithm representations. These techniques, when they are fully implemented, form the basis of a system which takes as input a serial presentation of the algorithm to be implemented, and gives as output an optimal SSIMD, static, or PSSIMD solution. If no optimal implementation of any of these classes exists, then the full cyclo-static compiler described above can be used to find an optimal solution.

RESEARCH ACCOMPLISHMENTS:

Work on the area of multiprocessor architectures for DSP has been centered in six areas: periodic scheduling theory; optimal realizations for parallel pipeline architectures; loop unwrapping for scheduling cyclic graphs; a new processor bound for graphs with bottlenecks; optimal realizations for complex DSP algorithms; and the development of the OSCAR-32 multiprocessor. In addition, a number of smaller miscellaneous projects have been accomplished.

- *Periodic Scheduling Theory*

Ph. D. thesis work performed by Helmut Forren has resulted in important generalizations and unifications of prior periodic scheduling methods. In prior work at Georgia Tech, three optimal periodic scheduling methods had been developed: SSIMD, cyclo-static and MCIMD. MCIMD (*Multi-Cyclic Instruction Multiple Data*) is an extension of cyclo-static schedules based primarily on the use of heterogeneous processing elements.

Recent work has resulted in the unification of SSIMD, cyclo-static and MCIMD as well as the more traditional scheduling methods of CPM[1],ASAP/ALAP[2], systolic array schedules and static pipeline schedules [?]. All of these schedules can be represented in a single unified form based on a *period matrix* and a *cycling vector*. Furthermore, any of the schedule types can be formally transformed into a generalized SSIMD[3] schedule, while a static schedule can be transformed into any of the other classes of schedules. Such transforms can be used to classify all deterministic parallel schedules into equivalence classes.

[1] Critical Path Method

[2] As Soon/Late As Possible

[3] For the case of homogeneous processors

The importance of this unification was that it showed that the generalized SSIMD schedule was the optimal class for homogeneous processors and that generalized *parallel SSIMD* (PSSIMD) was the optimal class for heterogeneous processors. Furthermore it provided a powerful conceptual framework that led to a simplified representation of schedules and a corresponding simplification of the scheduling algorithm. Based on this result, a preliminary, general purpose, parallel processing architecture based on a low order chorded ring has been proposed.

Other related work was the continued extension of performance bounds for multiprocessors. This included a new method to determine the true, achievable, minimum processor bound (for a given processing rate), as well as a causal throughput delay bound.

- *Scheduling Theory for Parallel Pipeline Architectures*

A new research topic which was initiated this year was the extension of cyclic multiprocessor scheduling techniques such as those used in the cyclo-static and generalized SSIMD compilers to pipeline and parallel pipeline architectures. This new theory is based on a set of transformations which represent pipeline and parallel pipeline architectures as parallel MIMD systems. These transformations represent individual pipeline processors (such as the AT&T DSP32 processor used in the OSCAR-32) as a number of *pseudo-processors* in a parallel structure. After the transformations, the result is a fully parallel architecture with no pipelined elements. Thus, parallel processor scheduling techniques can be applied directly to the transformed architectures to achieve optimal or near-optimal schedules. These multiprocessor realizations are then transformed back into their equivalent optimal or near optimal pipeline or parallel pipeline realization.

The multiprocessor representation needed to accommodate the transformed pipeline and parallel pipeline systems is nearly identical to that needed for parallel systems. The one difference is that the extended representation must allow for a synchronous clock skew between (groups of) individual processors. The leads to the concept of *clock classes*, which are the sets of all processors which share the same clock skew. In a traditional multiprocessor system, the clock skew is zero and all the processors belong to the same clock class. The effect of the clock classes is to provide a new set of constraints which are applied during the pruned tree search used in the cyclic scheduling algorithms.

Although this work is still in progress (this is the thesis area of C. P. Hong), it appears to have the potential for unifying parallel and pipelining scheduling theory.

- *Loop Unrolling for Code Generation* vs *Cyclo-Static Scheduling*

Prior work by S. H. Lee examined the issue of SSIMD schedules based on imperative program specifications. With the development of commercial VLIW computers, the question of the applicability of cyclo-static scheduling to code generation for scientific applications was investigated. Scientific code can often be characterized by nested "DO"

loops containing a number of arithmetic assignment statements[4]. When the number of iterations of the loop is large they can be conceptually approximated as infinite loops, thus making them amenable to the optimal cyclo-static scheduling technique for recursive flow graphs.

A preliminary investigation into these issues [?] showed that more traditional techniques of code generation for commercial supercomputers and mini-supercomputers is based on representing the "DO" loop as a directed acyclic graph (DAG) based on one iteration, or a few iterations in the case of the "advanced" technique of loop unrolling. The scheduling of the resulting DAG is fundamentally related to CPM methods. The representation of the loop as an acyclic graph of finite extent destroys inherent parallelism. A limited number of simple cases were investigated which showed a significant performance advantage of the cyclic scheduling approach of cyclo-static scheduling.

- *Processor Bounds for Graphs with Bottlenecks*

All of multiprocessor compilers which have been generated over the years as part of this research unit have depended on the concept of *processor bound.* This is simply a lower bound on the number of processors which can be utilized to achieve a particular synchronous multiprocessor realization at a particular iteration period. The processor bound was originally defined very simply as the ceiling of the total duration of the operations in a single iteration divided by the iteration period. This bound was found to work quite well for many DSP algorithms, and was hence of great utility. However, for the important class of adaptive (linear) systems, it was found that this simple bound was often not achievable.

Because the processor bound is used to strongly constrain the search space in the multiprocessor compilers, and because portions of the compilation are of combinational complexity, a tight processor bound is very important. Without a tight processor bound, the multiprocessor compilers can become so inefficient as to be unusable. An achievable processor bound can be found by construction, but this is generally as complex as the compiler itself. In his research, Pedro Gelabert has developed a new and much tighter processor bound which can be found much more efficiently. The procedure is base on a simple search techniques which identifies potential bottlenecks in the defining FSFG and corrects for them. Although this bound is not necessarily achievable, it has been found to give the tightest bound for several important classes of adaptive systems, including LMS gradient adaptive filtering and recursive least squares.

- *Optimal Multiprocessor Implementation for HMMs*

The training of a Hidden Markov Model (HMM) system is a computationally intensive, iterative procedure which can require dozens of iterations to optimize the model parameters. Unfortunately, the amount of computation required to train a HMM has made it difficult for researchers to optimize the model parameters in a reasonable amount

[4]Closely related work based on analyzing the "Lawrence Livermore Loops" can be found in [?]

of processing time. The basic (unscaled) Forward–Backward algorithm requires $O(s^2L)$ multiplies per iteration per training token, where s is the number of stages in the HMM, and L is the length of the training utterance. An algorithm developed by David Pepper reduces the time per iteration of this training procedure by effectively utilizing a ring of 2s processors.

The implementation is an extension of the SSIMD concept applied bi-directionally on a ring of synchronous MIMD machines. In effect, the solution utilizes two rate-optimal SSIMD implementation, counter rotating on the same ring. By synchronizing the two implementations with one another, it is possible to collect the results in such a way that only local communication is required.

- *Development of the OSCAR-32*

The OSCAR-32 synchronous multiprocessor system is the current target system for the multiprocessor research. It is hosted on personal computers, and is composed of processing elements designed and constructed at Georgia Tech. Several small OSCAR-32 systems have been configured (up to three boards and nine processors). A much larger system (sixteen boards and 48 processors) is currently under construction.

- *Miscellaneous Projects*

In addition a number of limited projects were undertaken during this time period. In support of the development of the OSCAR-32, initial efforts in support tools were undertaken. This included portions of a debugger (in conjunction with L. Heck, research assistant) and a simulator (in conjunction with S. Spalding, research assistant). A preliminary investigation of the applicability of processor bounds and cyclo-static schedules to the implementation of neural net algorithms was conducted (in conjunction with K. Truong, research assistant). An initial study of a design assistant for algorithm development for multiprocessors resulted in research into optimal special case FFT code generation (performed in conjunction with L. Heck, research assistant).

PUBLICATIONS:

Books and Journal Articles:

1. D. J. Pepper, T. P. Barnwell III and M. A. Clements, "A Ring Parallel Processor for Hidden Markov Model Training," submitted to *IEEE Transactions on ASSP*.

2. D. A. Schwartz, "Cyclo-Static Realizations, Loop Unrolling and CPM: Optimal Multiprocessor Scheduling," *To be published by Prentice Hall in 1988 as a chapter in a book edited by Stuart Tewksbury* (based on an invited presentation at the 1987 Princeton Workshop on Algorithm, Architecture and Technology Issues in Models of Concurrent Computations, Sept. 1987, Princeton, NJ).

Papers in Conference Proceedings:

1. H. F. Forren and D. A. Schwartz, "Transforming Periodic Synchronous Multiprocessor Programs," *Proc. of the International Conference on Acoustics, Speech and Signal Processing*, Dallas, TX, April, 1987.

2. S. J. A. McGrath, T. P. Barnwell III and D. A. Schwartz, "A WE-DSP-32 Based, Low Cost Multiprocessors for Cyclo-Static Implementations," *Proc. of the International Conference on Acoustics, Speech and Signal Processing*, Dallas, TX, April, 1987.

3. K. Nayebi, T. P. Barnwell III, and M. J. T. Smith, "Time Domain Conditions for Exact Reconstruction in Analysis/Synthesis Systems Based on Maximally Decimated Filter Banks," *1987 Southeast Symposium on System Theory*, Clemson, SC, March, 1987.

Honors and Awards:

1. T. P. Barnwell received "Rockwell Fellow Appointment", 1988.
2. T. P. Barnwell received "Georgia Tech Faculty Research Award for Outstanding Ph.D. Advisor," 1987.
3. T. P. Barnwell received "Sigma Xi Award as Outstanding Ph.D. Thesis Advisor," 1987.
4. Sae Hun Lee's Thesis received "Sigma Xi Award as Outstanding Ph.D. Thesis," 1987.

References

[1] H . F. Forren and D. A. Schwartz, "Transforming Periodic Synchronous Multiprocessor Programs," *Proc. of the International Conference on Acoustics, Speech and Signal Processing*, Dallas, TX, April, 1987.

[2] K . Hwang, "Pipeline Nets," *Proc. of the IEEE*, Jan., 1988.

[3] S . J. A. McGrath, T. P. Barnwell III and D. A. Schwartz, "A WE-DSP-32 Based, Low Cost Multiprocessors for Cyclo-Static Implementations, "*Proc. of the International Conference on Acoustics, Speech and Signal Processing*, Dallas, TX, April, 1987.

[4] D . A. Schwartz, "Cyclo-Static Realizations, Loop Unrolling and CPM: Optimal Multiprocessor Scheduling," *To be published by Prentice Hall in 1988 as a chapter in a book edited by Stuart Tewksbury* (based on an invited presentation at the 1987 Princeton Workshop on Algorithm, Architecture and Technology Issues in Models of Concurrent Computations, Sept. 1987, Princeton, NJ).

Work Unit Four

TITLE: Two-Dimensional Optical Information Processing

SENIOR PRINCIPAL INVESTIGATOR:

T. K. Gaylord, Regents' Professor

SCIENTIFIC PERSONNEL:

E. I. Verriest, Associate Professor
J. A. Buck, Assistant Professor
E. N. Glytsis, Graduate Research Assistant, (Ph.D. Candidate)
A. Knoésen, Graduate Research Assistant (Ph.D. Candidate)
T. A. Maldonado, A. R. O. Fellow (Ph.D. Candidate)
R. S. Weis, Graduate Research Assistant (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The long-term objective of this research is to develop broadly-based, theoretical and experimental knowledge of two-dimensional optical information processing including algorithms, architectures, systems, and devices. This brings together a range of concepts from basic physics to information processing in its most generalized form. Optical systems based on content-addressable memory processing, associative processing, Givens rotations, and hyperbolic rotations are being analyzed starting from basic physical principles and extending through experimental systems performance.

RESEARCH ACCOMPLISHMENTS:

- *Matrix Triangularization Using Givens Rotation Devices*

The elementary rotation matrix operation (and thus the Givens rotation) may be implemented in an optical micro-chip (integrated optics) form using an interdigitated-electrode-induced electro-optic grating at an intersection of dielectric waveguides. The use of arrays of the orthogonal transformation devices for performing matrix triangularization is illustrated and analyzed. With matrix triangularization, systems of equations, matrix inversion, least squares problems, eigenvalues and eigenvectors, discrete Fourier transform, and square root algorithms (in Kalman filtering and solving the Lyapunov and Riccati equations) can be implemented.

This research was published as an invited paper in *Computer*.

- *Residue Number System in Content-Addressable Memory Processing*

The need for ultra-high-speed computing for a variety of modern processing problems has generated new interest in using truth-table look-up techniques. Further, due to the frequently parallel nature of these processing problems, optical systems appear to be promising for these applications. The basic principles of truth-table look-up processing were reviewed. The issues of number representation, multilevel coding, and logical minimization were developed. Example fixed-radix and residue number representations were given with and without multilevel coding. Logical reduction techniques were discussed with examples. A comparison of the number of truth-table entries needed for 16-bit full precision addition and multiplication were given, illustrating the advantage of the multilevel coded residue number representation.

This research was published as a invited paper in the *Proc. SPIE.*

- *High Resolution Tunable Spectral Filtering*

A rigorous electromagnetic analysis method, using a 4×4 matrix formulation in combination with discrete Fourier transform techniques, was presented as a straightforward way of analyzing the optical transmission and reflection characteristics of anisotropic multilayered structures. Three examples illustrating the method were presented. First, the previous ellipsometric and polarimetric work of Zander *et al.* [Optik **70**, 6 (1985)] was extended to cases in which coupling between orthogonally polarized plane waves exists at interfaces. Second, Williamson's multiple-pass birefringent spectral filter [J. Opt. Soc. Am. **61**, 767 (1971)] was re-evaluated; results including and excluding interference effects are presented. Third, the design of a new, very narrow-an (typically 0.01 nm), tunable spectral filter called the Fabry-Perot/Solc filter was introduced. Several versions of the Fabry-Perot/Solc filter, each employing different materials, were analyzed. One version exhibits a total tuning range of 40 nm, and another version has an effective finesse of approximately 1300.

This research was published in *Journal of the Optical Society of America.*

- *Spatial Light Modulator Design and Evaluation*

Digital optical data storage and processing are rapidly increasing in technological importance. The magneto-optic spatial light modulator (MOSLM) is a relatively low cost optical parallel input device that is capable of binary amplitude or binary phase modulation of each pixel. Thus it is well matched to digital optical technology. However, potential problems associated with its use include: lack of a design for a general minicomputer interface, lack of interactive data-page-file generation software, lack of ability to switch single pixels in some cases, lack of remote-from-computer operation capability, spurious pixel switching, and catastrophic failure due to thermal effects. The hardware and software components of a versatile minicomputer interface that has been successful in overcoming

all of these problems are described. This interface allows easy data entry of entire data pages or single pixels and minimizes crosstalk and noise developed over long cable lengths. In tests, it has provided highly stable operational characteristics.

These results were published in *Review of Scientific Instruments.*

- *Analysis Interdigitated Electrodes on Electro-Optic Waveguides*

Integrated optical interdigitated-electrode devices are used to diffract light and to launch acoustic waves. The electric field and the permittivity and strain tensors induced by a voltage applied to periodic interdigitated electrodes of finite thickness on the surface of an anisotropic electro-optic crystalline waveguide were calculated rigorously. The extremely important existence of a buffer layer between the electrodes and the waveguide occurring in practical devices was included in the analysis.

This work was published in *Journal of Lightwave Technology.*

- *Zero-Reflectivity Surface Relief Gratings on Lossy Materials*

The required thickness and complex refractive index of single homogeneous layers on lossy substrates to produce zero reflectivity are calculated by a rigorous impedance matching approach. The analysis is applicable to both TE and TM polarization and to any angle of incidence. The filling factor and the groove depth of a rectangular-groove grating equivalent to a single homogeneous lossy layer in the long wavelength limit are calculated. The method reduces to that previously found for dielectric surface-relief gratings in the limit of no losses. The anti-reflection behavior is verified for the gratings using the rigorous (without approximations) coupled-wave analysis of metallic surface-relief grating diffraction. It is shown that multiple zero-reflectivity solutions exist for both TE and TM polarizations and for any angle of incidence for an arbitrary complex-refractive-index substrate. Example zero-reflectivity gold gratings for an incident freespace wavelength in the range from $\delta_0 = 0.44\mu m$ to $12.0\mu m$ are presented. For the longer wavelengths, the behavior of the gold approaches that of a perfect conductor and the required filling factor approaches zero for TE polarization and unity for TM polarization.

This research was published in *Applied Optics.*

- *Grating Diffraction*

The diffraction by one or an arbitrary number of cascaded anisotropic planar gratings with slanted fringes, was analyzed using rigorous three-dimensional vector coupled-wave theory. Arbitrary angle of incidence and polarization are treated. The existence of uniaxial external regions and the treatment of both phase and amplitude anisotropic slanted gratings are included in the analysis. The anisotropy as well as the three-dimensionality of the problem cause coupling between orthogonally polarized waves. The Bragg conditions for

various combinations of ordinary (O) and extraordinary (E) polarized waves are quantified. Example calculations were presented for single anisotropic gratings (a lithium niobate hologram in air and an interdigitated-electrode-induced electro-optic grating in an optical waveguide), for two cascaded anisotropic gratings (a pair of interdigitated-electrode-induced gratings satisfying the OOO forward Bragg condition, the EEE forward Bragg condition, and the OOO backward Bragg condition), and for multiple cascaded gratings (a lithium niobate hologram with depth modulation). The same analysis applies in the limiting cases of: isotropic materials, grating vector lying in the plane of incidence, etc. Applications for this analysis include optical storage, switching, modulation, deflection, and data processing.

This research was published in *Journal of the Optical Society of America*.

PUBLICATIONS:

Ph.D. Theses (Completed):

1. André Knoesen, "Guided Modes in Anisotropic Dielectric Planar Waveguides," Ph.D. Thesis, Georgia Institute of Technology, Atlanta, Georgia, May 1987.

2. Elias N. Glytsis, "Interdigitated Electrodes and Anisotropic Diffraction Analysis of Phase and/or Lossy Gratings for Bulk and Integrated Applications," Ph.D. Thesis, Georgia Institute of Technology, Atlanta, Georgia, November 1987.

3. R. Steve Weis, "Electromagnetic Transmission and Reflection Characteristics of Anisotropic Multilayered Structures," Ph.D. Thesis, Georgia Institute of Technology, Atlanta, Georgia, December 1987.

Journal Articles (Published or Accepted):

1. E. N. Glytsis, T. K. Gaylord, and M. G. Moharam, "Electric field, permittivity, and strain distributions induced by interdigitated electrodes on electro-optic waveguides," *Journal of Lightwave Technology*, vol. LT-5, pp. 668-683, May 1987.

2. M. M. Mirsalehi and T. K. Gaylord, "Residue number systems in content-addressable memory processing," *Proceedings SPIE*, vol. 752, pp. 175-178, 1987.

3. T. K. Gaylord and E. I. Verriest, "Matrix triangularization using arrays of integrated Givens rotation devices," *Computer*, vol. 20, pp. 59-66, December 1987. (invited)

4. T. K. Gaylord, E. N. Glytsis and M. G. Moharam, "Zero-reflectivity homogeneous layers and high spatial-frequency surface-relief gratings in lossy materials," *Applied Optics*, vol. 26, pp. 3123-3135, August 1, 1987.

5. E. N. Glytsis and T. K. Gaylord, "Rigorous three-dimensional coupled-wave diffraction analysis of single and cascaded anisotropic gratings," *Journal of the Optical Society of America A*, vol. 4, pp. 2061-2080, November 1987.

6. R. S. Weis, and T. K. Gaylord, "Electromagnetic transmission and reflection characteristics of anisotropic multilayered structures," *Journal of the Optical Society of America A*, vol. 4, pp. 1720-1740, September 1987.

7. A. Knoesen, N. F. Hartman, T. K. Gaylord and C. C. Guest, "Minicomputer interface for magneto-optic spatial light modulator," *Review of Scientific Instruments*, vol. 58, pp. 1843-1851, October 1987.

8. T. K. Gaylord and A. Knoesen, "Passive integrated optical anisotropy-based devices," *Journal of Modern Optics*, accepted for publication in 1988. (invited)

9. A. Knoesen, T. K. Gaylord and M. G. Moharam, "Hybrid guided modes in uniaxial dielectric planar waveguides," *Journal of Lightwave Technology*, vol. LT-6, accepted for publication in 1988.

Papers in Conference Proceedings:

1. T. K. Gaylord, E. N. Glytsis, M. G. Moharam and W. E. Baird, "Antireflection surface-relief gratings on dielectric and lossy substrates," (Abstract) *Journal of the Optical Society of America*, vol. 4, no. 13, pg. P92, December 1987.

2. E. N. Glytsis and T. K. Gaylord, "Antireflection dielectric overcoated high spatial-frequency rectangular-groove surface-relief gratings on Lossy Materials," (Abstract) *Journal of the Optical Society of America A*, vol. 4, pp. P18, December 1987.

3. A. Knoesen and T. K. Gaylord, "Integrated optical anisotropic waveguides: Cutoff conditions and anisotropy-based devices," (Abstract) *Journal of the Optical Society of America A*, vol. 4, pg. P6, December 1987.

4. R. S. Weis and T. K. Gaylord, "Electro-optically tunable narrow-band Fabry-Perot/Solc filter design," (Abstract) *Journal of the Optical Society of America A*, vol. 4, pg. P49, December 1987.

Patent Applications:

1. T. K. Gaylord, E. I. Verriest, and M. M. Mirsalehi, "Integrated Optical Givens Rotation Device," Patent application, Record of invention no. 899, May 1987.

2. T. K. Gaylord, E. N. Glytsis, M. G. Moharam and W. E. Baird, "Technique for producing antireflection grating surfaces on dielectrics, semiconductors, and metals," Patent application, Record of invention no. 953, September 1987.

Honors and Awards:

T. K. Gaylord was honored in the following ways during 1987.

1. Received "Georgia Tech Faculty Research Award for Outstanding Research Authorship," 1987.
2. Received "Engineer of the Year in Education," Award from Georgia Society of Professional Engineers, 1987.
3. Elected to Academy of Electrical Engineering sponsored by the University of Missouri-Rolla, 1987.
4. Received the "Meritorious Service Award" from the IEEE Education Society, 1987.
5. Received the "Engineer of the Year" Award from Georgia Society of Professional Engineers, 1988.

TECHNOLOGY TRANSFER:

- Invited Seminar: T. K. Gaylord, "Optical computing," Technology Base Investment Strategy Conference sponsored by U.S. Army, Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland, February 1988.
- Analysis of integrated optical waveguide devices for high-speed signal processing applications is being performed for the U.S. Army Materials Technology Laboratory, Watertown, Massachusetts.

Work Unit Five

TITLE: Two-Dimensional Optical/Electronic Signal Processing

SENIOR PRINCIPAL INVESTIGATOR:

William T. Rhodes, Professor

SCIENTIFIC PERSONNEL:

S.D. Goodman, Graduate Research Assistant (Ph.D. candidate)
J.N. Hereford, Graduate Research Assistant (Ph.D. candidate)
R.W. Stroud, Graduate Research Assistant (Ph.D. candidate)
J. van der Gracht, Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The long term scientific objective of this research is to gain a good understanding of the capabilities and limitations of hybrid optical/electronic methods for high throughput processing of 2-D signal information and to develop new and widely applicable techniques based on such methods. Emphasis is placed on establishing the capabilities of systems that mate well with digital signal processing systems.

RESEARCH ACCOMPLISHMENTS:

- *Linear and Nonlinear Image Processing*

Optical Morphological Transformations and Extensions. During the report period we completed an experimental demonstration of time-sequential threshold decomposition combined with optical morphological transformations (e.g., erosions, dilations) to perform median filtering on gray-scale imagery. This material has been accepted for publication as an invited paper in *Optical Engineering* [1] and will be presented at a national conference [2]. Current work is on extensions of threshold-decomposition nonlinear filtering that use gray-scale kernals as opposed to binary kernals in the optical morphology portion of the processing operation. One application is to skeletonization of input patterns. Gray-scale kernals can be implemented with electronic processors only at considerable extra expense in hardware and processing time, whereas in the optical implementation they are no more difficult to implement than binary kernals. It is thus in this area we expect the optical approach to nonlinear filtering to compare most favorably with the all-electronic approach. We have begun looking at the prospects for using a membrane-type spatial light modulator, of the kind currently under investigation at the Naval Research

Laboratory, in high-speed threshold decomposition. It appears that these devices can be quite fast (switching times of tens of microseconds) if optically addressed. With such operating speeds they could be used to implement full image processing operations (e.g., median filtering) on high-density imagery at TV frame rates.

Partially Coherent Optical Systems for Image Enhancement. We believe that full two-dimensional simulations of partially-coherent imaging operations are essential to our understanding of the complicated nature of these systems as applied to image enhancement. As a consequence, we have looked at alternative mathematical models for Koehler-type partially coherent imaging systems from the standpoint of computer simulation. The problem is significant because of the considerable computational load involved in even simple simulations. One major achievement has been the clarification of the Nyquist sampling conditions that apply to the source and pupil distributions in such bilinear (as opposed to linear) systems. We have shown that the minimum sampling rate depends on the reciprocal of the smaller of the width of the object and the width of the imaging system coherent point spread function. Earlier published analyses suggested that only the object width was of concern. This clarification will allow us to sample at the minimum rate necessary for simulation results free from aliasing errors. Our analysis has been written up and submitted for journal publication [3]. Work during the coming months will center on reducing the computational load for system simulation by using singular value decomposition and truncated outer-product expansions for the source, object, and pupil distributions.

Three-Dimensional Image Processing. In connection with our interest in processing of volumetric images, we have investigated the performance of telecentric, confocal imaging systems and shown that in both a geometrical (ray) optics sense and a diffraction (wave) optics sense these systems are fully space-invariant, so long as attention is restricted to a conical region of object space. This means that the 3-D image distribution $i(x, y, z)$ produced by such a system can be represented by the 3-D convolution

$$i(x,y,z) = o(x,y,z) *** h(x,y,z),$$

where $o(x, y, z)$ represents the 3-D object distribution and $h(x, y, z)$ the 3-D impulse response of the imaging system. This expression is valid for both coherent and incoherent imaging, the former being linear in wave amplitude, the latter in wave intensity. This space invariance has been alluded to in several publications but never, to our knowledge, been verified analytically. We plan to submit our analysis for publication in a refereed journal soon. Work in the coming months will center on restoration of degraded volumetric imagery and on the application of telecentric confocal imaging systems to the optical processing of 3-D imagery.

Processing Applications of Symbolic Substitution. Optical hardware for symbolic substitution is under serious consideration for parallel optical computing applications. Symbolic substitution replaces chosen patterns of ones and zeros in a binary array with other chosen patterns of ones and zeros. Implemented with specialized substitution rules, sym-

bolic substitution can be applied to the processing of images that are represented in binary form. During the report period we completed a basic investigation of such applications. Important operations investigated include (1) nonlinear filtering operations applied to shapes (morphological transformations, including erosion, dilation, opening, closing) and (2) linear filtering operations applied to binary digital representations of continuous-tone images. A paper based on this work has been accepted for publication in *Applied Optics* [4]. Examples included in the paper are a nonlinear noise-removal operation, thresholding, a gradient operator, and convolution. The results of an engineering study of system complexity for linear filtering operations are also presented in the paper. Our reason for considering these applications of symbolic substitution is simple: if symbolic substitution is successful in general-purpose computation, the necessary hardware will be available for special-purpose image processing systems as well.

- *Two-Dimensional Optical Processing of One-Dimensional Signals*

Generalized Falling-Raster/Folded Spectrum Analyzer. During the report period we investigated a family of raster mappings for the optical spectrum analysis of broadband signals. The family contains as one member the conventionally-used falling raster. In a paper recently submitted for publication [5] we develop an analytical model (appropriate for space-integrating coherent optical spectrum analyzers) for the raster input and the Fourier plane distribution. The family of raster mappings and its Fourier transform is shown to be a continuous analog of the I. J. Good fast Fourier transform algorithm. Optical signal processing hardware implications of this generalized family of relationships is currently under investigation.

Acousto-optic systems for outer-product processing. In developing hardware for outer-product-based signal processing experiments we have taken a commercially- available 2-D acousto-optic scanner system built by Newport Electro-Optic Systems Company and modified it for optimal performance in signal processing applications. The associated device analysis, which is made complicated by the birefringence and optical activity of the shear-wave-mode TeO_2 Bragg cells used, has lead to several papers that have been submitted for publication [6-8]. One paper [6] describes basic design considerations for the processor. The other two papers report on general acousto-optic design techniques we developed in the course of this work.

PUBLICATIONS:

Papers Submitted for Publication:

1. James M. Hereford and William T. Rhodes, "Nonlinear Optical Image Processing by Time-Sequential Threshold Decomposition," accepted for publication in *Optical Engineering*.

2. James M. Hereford and William T. Rhodes, "Nonlinear Optical Image Processing by Threshold Decomposition," to be published in *Hybrid Image and Signal Processing*, D. Casasent and A. Tescher, eds. (*Proceedings of the SPIE, vol. 939, 1988*).

3. Joseph van der Gracht and William T. Rhodes, "Source Sampling for Incoherent Imaging and Spatial Filtering," submitted to *Applied Optics*.

4. Stephen D. Goodman and William T. Rhodes, "Symbolic Substitution: Applications to Image Processing," accepted for publication in *Applied Optics*.

5. David N. Sitter and William T. Rhodes, "Generalization of the Falling Raster-Folded Spectrum Relationship," submitted to *Applied Optics*.

6. Jieping Xu and William T. Rhodes, "Calculation of Effective Acousto-Optic Coefficient by Abbreviated Subscript Formalism," submitted for publication in *Applied Optics*.

INTERACTIONS WITH DOD LABS:

- Dr. L. Flax, Naval Coastal Systems Center, 30 September 1987, regarding applications of nonlinear optical filtering methods to floating mine detection.

- P. Denzil Stilwell, Radar Division, Naval Research Laboratory, 11 December 1987, regarding optical processing in phased-array radar systems.

Work Unit Six

TITLE: Electromagnetic Measurements in the Time and Frequency Domains

SENIOR PRINCIPAL INVESTIGATOR:

G. S. Smith, Professor

SCIENTIFIC PERSONNEL:

W. R. Scott, Jr., Assistant Professor
M. Gouker, Graduate Research Assistant (Ph.D. Candidate)
J. G. Maloney, Graduate Research Assistant (Ph.D. Candidate)
G. P. Zhou, Graduate Research Assistant (Ph.D. Candidate)

SCIENTIFIC OBJECTIVE:

The broad objective of this research is to develop new methodology for making electromagnetic measurements directly in the time domain or over a wide bandwidth in the frequency domain. This research includes the development of the theoretical analyses necessary to support the measurement techniques. One aspect of the research is the systematic study of radiating structures placed near or embedded in material bodies. In a practical situation, the radiator might serve as a diagnostic tool for determining the geometry, composition or electrical constitutive parameters of the body.

RESEARCH ACCOMPLISHMENTS:

- *Pulse Excited Antennas Near a Material Interface*

Ground penetrating radar systems have been proposed for many applications; these include the detection of mines and buried unexploded ordinance, the location or buried utilities and the mapping of subsurface geological structure. The systems generally make use of a temporarily short, wide bandwidth, pulse. The pulse is transmitted and received by one or more antennas located above the surface of the earth.

The characterization and design of antennas for this application are complicated by two factors: the broad-band requirements and the effect of the air/earth interface on the performance of the antenna. Two types of antennas have generally been used for systems of this kind: dipole type antennas located very close to the air/earth interface and TEM horn antennas located at a larger distance from the air/earth interface.

We have initiated a research program to study new antennas for this application. Scale model facilities are being constructed for measuring the performance of antennas over an interface between air and a model earth. Sensors and targets embedded in the model earth are used to evaluate the field of the antenna.

One-third size scale model antennas are used with this system; full size antennas would generally require larger test facilities than can be accommodated in our laboratory. Techniques have been developed for correcting errors in the automated time-domain instrumentation used with this system.

• *Materials for Electromagnetic Scale Models*

Electromagnetic scale models are of value in the design and testing of electromagnetic systems that are on a scale too large or too small for routine laboratory use. For example, the performance of antennas over or buried in the earth can be evaluated in the laboratory using reduced size scale models operated at frequencies higher than those used for the actual antennas. For this model, a material is needed that will model the electrical properties of the earth. Scale models with increased size are also used; a microscopic antenna on a substrate may be modeled by a larger antenna operated at a frequency lower than that for the actual antenna. A material is then needed that can model the electrical properties of the substrate. Clearly it is desirable to have a series of materials with a range of electrical properties or mixtures of materials with adjustable electrical properties for use in scale models.

In this research, simple emulsions are examined as materials with adjustable electrical constitutive parameters. These emulsions are mixtures of oil, saline solution, and a suitable stabilizing agent (emulsifier). Since the relative permittivities of oil and water are around two and eighty, respectively, a large range of permittivity can be obtained for the emulsions. The conductivity of the emulsions can be adjusted by changing the normality of the saline solution. A series of oil-in-water emulsions (oil droplets in water), suitable for use in scale models, was developed; this includes the selection of an appropriate emulsifier. The electrical constitutive parameters of these emulsions are adjustable over wide ranges, and are predictable from a simple formula. As an example, an emulsion that is a scale model for red-clay earth was formulated. This emulsion matches the electrical constitutive parameters of the clay, including the dispersion in the conductivity, over a ten-to-one frequency range. This emulsion is being used in the system described above for studying pulse excited antennas. A paper describing this research has been submitted for publication.

PUBLICATIONS

Journal Articles (published or accepted)

1. G. S. Smith and W. R. Scott, Jr., "Measurement of the Electrical Constitutive Parameters of Materials Using Antennas, Part II," *IEEE Trans. Antennas and Propagation*, vol. AP-35, pp. 962-967, August 1987.

2. G. S. Smith and W. R. Scott, Jr., "The Use of Emulsions to Represent Dielectric Materials in Electromagnetic Scale Models," submitted to *IEEE Trans. Antennas and Propagation.*

3. W. R. Scott, Jr., "A General Program for Plotting Three-Dimensional Antenna Patterns," submitted to *IEEE Trans. Antennas and Propagation.*

Papers in Conference Proceedings

1. G. S. Smith and W. R. Scott, Jr., "A Simple Method for the In Situ Measurement of the Electrical Properties of the Ground," *1987 International IEEE Antennas and Propagation Symposium*, Blacksburg, VA, June 1987.

2. W. R. Scott, Jr., "A General Program for Plotting Three-Dimensional Antenna Patterns," *1987 International IEEE Antennas and Propagation Symposium*, Blacksburg, VA, 1987.

TECHNOLOGY TRANSFER:

During the period of the contract, a study entitled "Hardened Antenna Technology Assessment" was performed for the Air Force (RADC, Griffiss AFB). This study made use of information developed on the Joint Services Electronics Program. The Air Force (RADC, Hansom AFB) also partially supported the work under item 2 above.

Work Unit Seven

TITLE: Automated Radiation Measurements for Near- and Far-Field Transformations

SENIOR PRINCIPAL INVESTIGATOR:

E. B. Joy, Professor

SCIENTIFIC PERSONNEL:

R. E. Wilson, Graduate Research Assistant (Ph.D. Candidate)
Mike G. Guler, (M.S. Candidate)
Darryll G. Wright (M.S. Candidate)
Donald Black (Ph.D. Candidate)
Angela R. Dominy (Ph.D. Candidate)
Joe Epple (M.S. Candidate)

SCIENTIFIC OBJECTIVE:

The long term objective of this research is to understand the near field and far field coupling between antennas in the presence of scatterers. Special emphasis is placed on determination of limits of accuracy in the measurement of the fields radiated or scattered by an antenna-under-test by a second antenna and to develop techniques and computer algorithms for compensation of such measurements due to known geometrical or electromagnetic anomalies.

Three application areas are pursued: a) antenna measurements, where the effects of scatterers are suppressed or compensated, b) scattering measurements, where the effects of scatterers are enhanced, and c) radome measurement, where the effects of the scatterer (the radome) are of equal importance to the antenna measurement.

RESEARCH ACCOMPLISHMENTS:

- *Shaped Edge Serrations for Improved Reflector Performance*

A new edge treatment for electromagnetic reflectors was developed which produces less wide angle scattering than previously used edge treatments. The new edge treatment allows a wide variety of field transition functions to be realized in an average sense. This new technology has been applied to the design of an improved compact antenna range reflector, resulting in a lower cost, better quiet zone performance range. This range is currently under construction at Ft. Huachuca, Arizona. This technology is currently being applied to the design and construction of a paraboloidal reflector antenna to achieve low, wide angle, sidelobe levels.

• *Radome Anomaly Detection Using Near-Field Measurements*

The theory and technique for the measurement of electromagnetic imperfections (anomalies) in radome structures has been developed and demonstrated. The technique involves "backward transforming" near-field measurements taken on a spherical surface near the enclosed antenna and radome. These measurements are "backward transformed" to the known outer surface shape of the radome and compared to the same fields of a "standard" or anomaly-free radome. The magnitude and phase differences between these two backward transformed fields indicate the size and location of the anomalies.

This work, plus other publications and technology transfers of the principal investigator are summarized below.

PUBLICATIONS:

Books or Chapters in Books

1. E. B. Joy, "TV Receiving Antennas," Chapter 6, *Antenna Applications Reference Guide*, Johnson and Jasik (Eds.), McGraw-Hill Book Company, 1987.

2. E. B. Joy, "Millimeter-Wave Radomes," Chapter 11, *Principles and Applications of Millimeter-Wave Radar*, N. C. Currie (Ed.), Artech House, 1987.

Short Course Text

1. E. B. Joy, "Helical Antennas," "Frequency Independent Antennas," "VHF and UHF Antennas," "Radomes," and "Antenna Measurements," Chapters of *Antenna Engineering*, E. B. Joy (Editor), Georgia Institute of Technology, 1987.

Journal Articles (published or accepted)

1. E. B. Joy, "Near-Field Range Qualification," accepted for publication in the *IEEE Transactions on Antennas and Propagation.*

2. E. B. Joy, "A Brief History of the Development of the Near- Field Measurement Technique at the Georgia Institute of Technology," for publication in the *IEEE Transactions on Antennas and Propagation.* (Invited)

Papers in Conference Proceedings

1. E. B. Joy and R. E. Wilson, "Shaped Edge Serrations for Improved Compact Range Performance," *Proceedings of the 1987 Antenna Measurement Techniques Association Meeting*, Seattle, WA, September 28 - October 2, 1987, pp. 55-62.

2. E. B. Joy, M. G. Guler, C. H. Barrett, A. R. Dominy, and R. E. Wilson, "Near-Field Measurement of Radome Anomalies," *Proceedings of the 1987 Antenna Measurement Techniques Association Meeting*, Seattle, WA, September 28 - October 2, 1987, pp. 235-240.

3. L. Jofre, E. B. Joy, and R. E. Wilson, "Antenna Pattern Correction for Range Reflections," *Proceedings of the 1987 Antenna Measurement Techniques Association Meeting*, Seattle, WA, September 28 - October 2, 1987, pp. 63-68.

4. E. B. Joy, "Antenna System Performance Testing," *Proceedings of the Missile/Projectile/Airborne Test Instrumentation Antenna Workshop*, Atlanta, GA, October 6-8, 1987. (Invited; not yet published.)

TECHNOLOGY TRANSFER:

U. S. Army Electronic Proving Ground, Fort Huachuca, Arizona: The spectral analysis technique for the evaluation of reflector surfaces and the shaped edge serrations for improved quiet zone performance developed under JSEP sponsorship is currently being used in the design of a large outdoor compact antenna measurement range at Fort Huachuca, Arizona.

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